Lunar COTS: An Economical and Sustainable Approach to Reaching Mars

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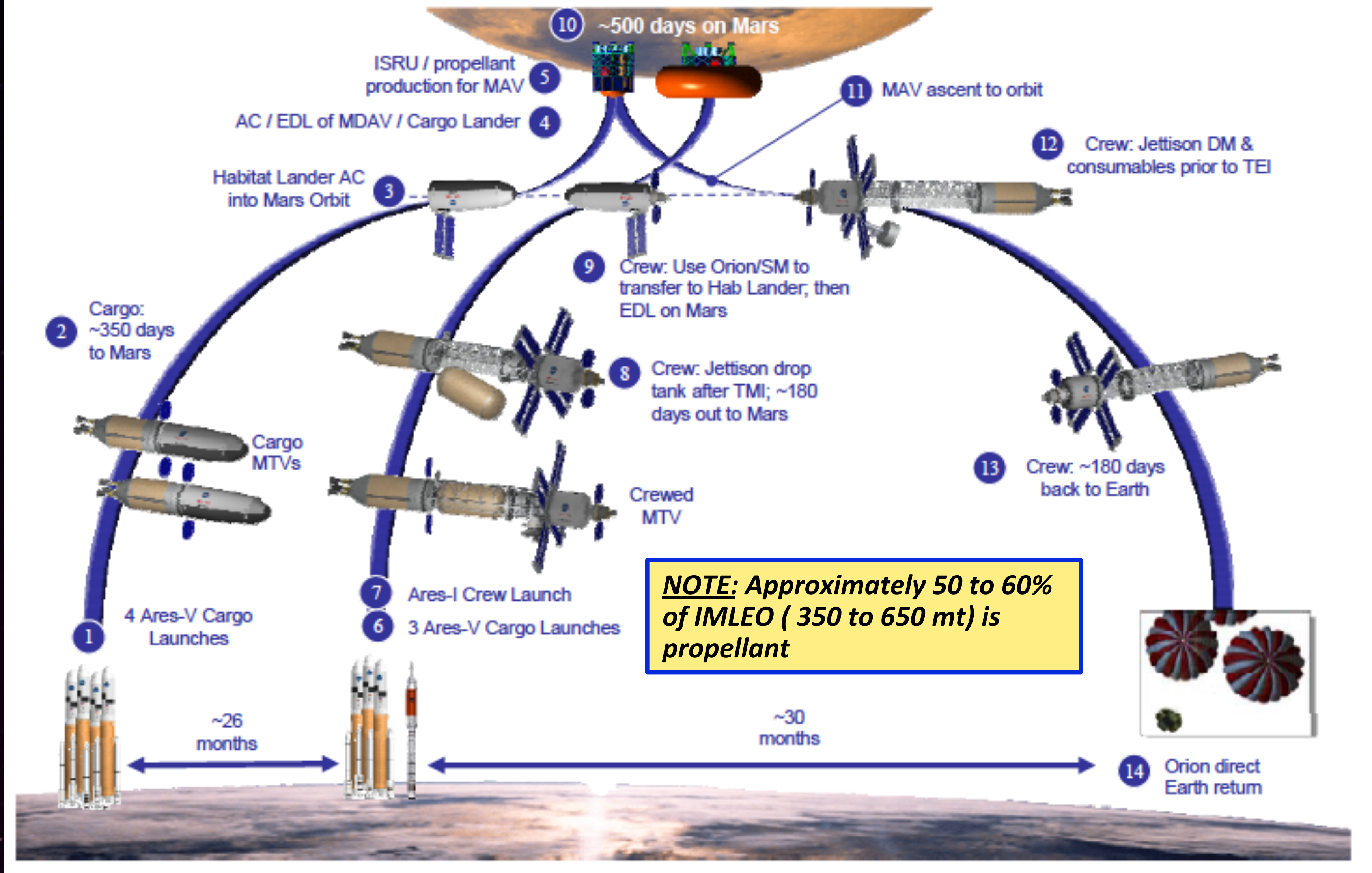
Introduction

- President Obama's 2010 National Space Policy set the following goal for NASA:
  - By the mid-2030's, send humans to orbit Mars and return them safely to Earth.
- For the first time, the NASA Strategic Plan of 2014 included human missions to Mars as a goal.

- NASA's Mars Architecture Working Group (MAWG) released a Mars Design Reference Architecture 5.0 (DRA5) back in 2009.
  - DRA5 estimated that 7 to 12 heavy-lift launch vehicles would be needed per Mars campaign.
  - This architecture resulted in very high cost estimates far exceeding NASA's budgets for its development and operational phases.
- Recently, NASA initiated the Evolvable Mars Campaign to evolve plans, conduct trade studies and investigate architectures for transporting humans to Mars.

Mars DRA5 Architecture



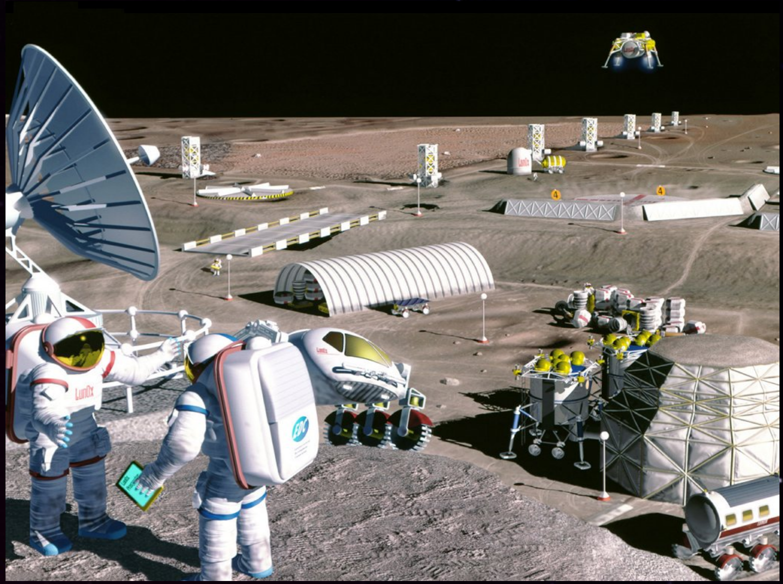
***NOTE:* Approximately 50 to 60% of IMLEO (350 to 650 mt) is propellant**

Motivation for Lunar COTS

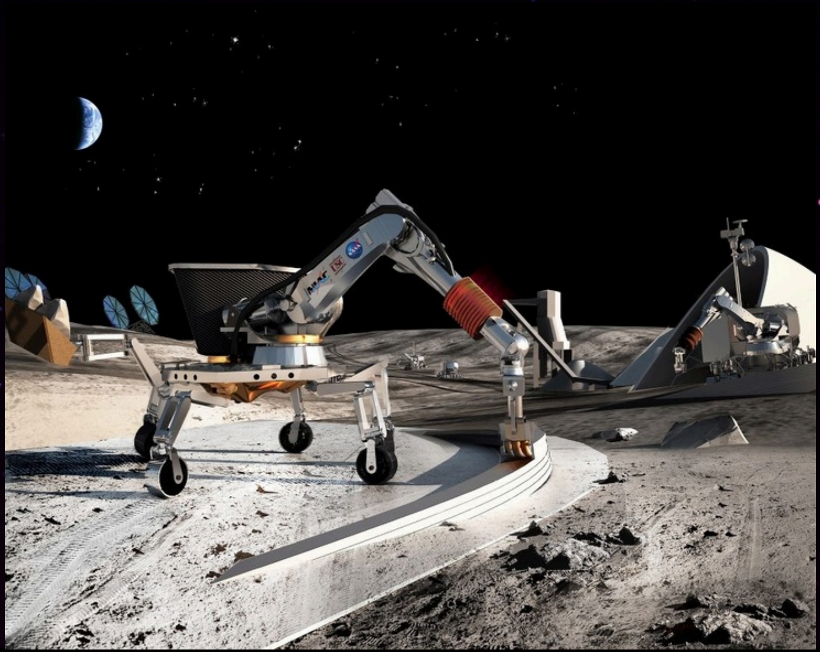
- Commercial opportunity exists for delivering the propellant needed to Mars Transfer Vehicles at Cis-Lunar Destinations (L1, L2 or LDRO).
    - NASA MSFC 2010 Report estimated that only ***4 Ares V launch vehicles*** would be necessary for each mission if the propellant was delivered separately to a LEO propellant tanker.

Recommendations for an economical and sustainable approach to achieving human missions to Mars:

- Use Cis-Lunar space as a nearby testbed for maturing and demonstrating capabilities for future Mars transportation systems.
- Leverage international and commercial participation as much as possible.
- Learn to "live off the land" and develop ISRU capabilities.
- Demonstrate value and economic benefit to important stakeholders and the public .
- Create a thriving Cis-Lunar economy to support and sustain future human missions to Mars.



Lunar Commercial *Transfer* Services (LCOTS)

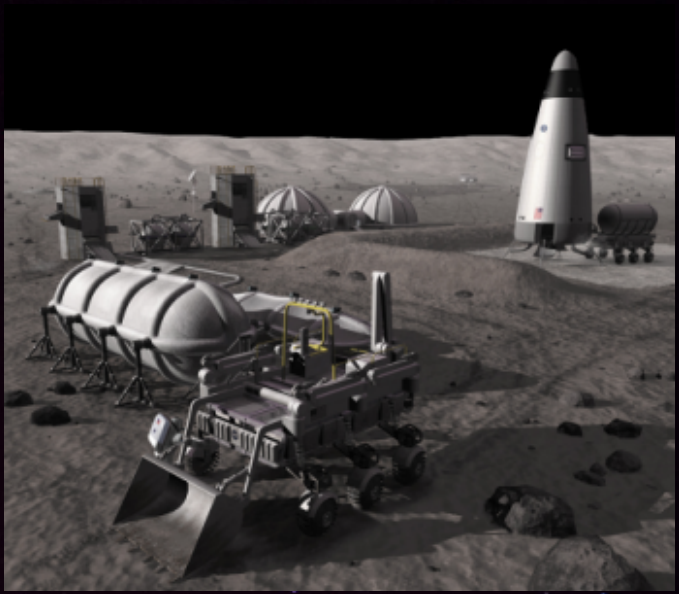


GOALS

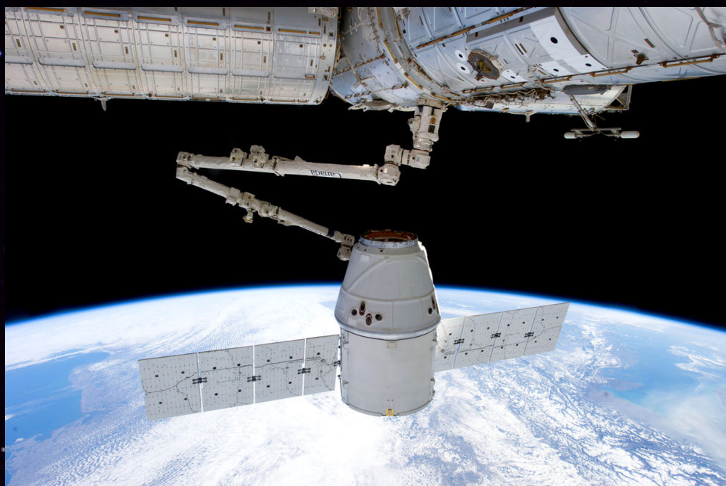
- Establish affordable, cis-lunar capabilities and services by partnering with industry to share development and operational costs.
- Enable NASA to develop an economical and sustainable Exploration Architecture.
- Encourage creation of new markets in cis-lunar space to further reduce ops costs.

PRIMARY OBJECTIVES

- Demonstrate cis-lunar capabilities for lunar transportation and ISRU production.
- Reduce technical/operational risk and life-cycle costs to Mars mission concepts by developing key cis-lunar capabilities;
- Incentivize commercial partners to target other markets outside Government to make their business case close.



NASA COTS/CRS Accomplishments



- Under COTS Space Act Agreement, SpaceX develops and enters into operation Falcon 9 launch vehicle and Dragon spacecraft;
- In 2012, SpaceX becomes first private company to deliver cargo to ISS under CRS contract.
- To date, SpaceX has successfully launched 6 cargo delivery missions to ISS.

- In 2008, NASA COTS selects Orbital Sciences Corp. to develop Antares launch vehicle and Cygnus spacecraft;
- In 2013, Orbital completes final demonstration mission to ISS under COTS;
- To date, Orbital has successfully launched 2 cargo delivery missions to ISS.

NASA COTS Lessons Learned

- Recent NASA study showed a ***20-to-1 reduction in costs*** for Space-X's Falcon 9 development.
- Using the NASA-AF Cost Model (NAFCOM), NASA estimated that Falcon 9 would have cost approximately $4B using traditional FAR contracts vs $200M actual costs to NASA.

Best Practices from NASA COTS:

1. NASA and commercial partners share cost and risks to demonstrate new capabilities for mutual benefit.
2. NASA makes long-term commitments to procure commercial services to help secure private investments.
3. NASA encourages commercial partners to target other markets outside Government to make their business case close.
4. NASA uses SAA's to enter into partnership with commercial partners to offer maximum flexibility in design solutions.
5. NASA includes pay-on-performance milestones in SAA's to provide several off-ramps and reduce programmatic risk.
6. Commercial partners retain Intellectual Property (IP) rights; operates and owns final product(s).

Criteria for Assessing LCOTS Capabilities

Criteria	Description	Hi/Med/Lo Definitions
Industry Maturity/Capability	Readiness or maturity level of industry capability to perform successfully in an operational space environment.	High – TRL 6 or above Med – TRL 4 or 5 Low – TRL 3 and below
Viable Companies	Number of viable companies that exemplify strong financial and technical capabilities and ability to raise significant investment funds for proposed capability demonstration.	High – 3 or more companies Med – 1 or 2 companies Low - 0
Significant Market	Measure of potential for emergence of near-term markets (within 5 years) beyond NASA's needs to enable cost sharing (private financing) and cost-effective pricing.	<u>High</u> – Over $500M markets in next 5 years <u>Med</u> – Between $100M to $500M markets in next 5 years <u>Low</u> – Emergence of markets in over 5 years
Positive Return on Investment (ROI)	Measure of potential for positive ROI includes level of affordability to fully develop capability, proposed price point for capability and overall business plan to achieve ROI.	<u>High</u> – proposed business plans are sound and reasonable <u>Med</u> – proposed price points are achievable <u>Low</u> – no evidence of credible business plan or price point
Risk Reduction for Mars	Measure of potential to reduce technical, operational or cost risk for capability that may be a critical element of a Mars architecture.	<u>High</u> – 80% or greater likelihood that capability will reduce risk Mars missions <u>Med</u> – 40 - 80% likelihood <u>Low</u> – less than 40%

Preliminary Assessment of Potential Capability Candidates

Phase	Capability-Description	Industry Capability/ Maturity	Viable Companies	Significant Market Beyond NASA	Potential for Positive ROI	Risk Reduction for Mars
Phase 1	**Lunar Landers** – Delivers payload < 1 mt to surface	High	High	High	High	Medium
Phase 1	**Lunar Rovers** - small rovers for traversing distances up to 50 km	High	High	High	High	Medium
Phase 1	**Instrument package**– for prospecting resources and identifying hazards	Medium	Low	Low	Medium	Medium
Phase 1	**ISRU Demo-** H2O or other resources extraction	Medium	Medium	High	Medium	High
Phase 2	**Comm and Navigation Satellites** – to enable large-scale ISRU operations	High	High	High	High	Medium
Phase 2	**Solar or Nuclear Power Stations** – for sunlit or dark operations	Medium	Medium	High	High	High
Phase 2	**Pilot-Scale ISRU Production** – to produce 1 or 2 mt of H2O or LOX/LH2	Medium	Medium	Medium	Medium	High
Phase 2	**Reusable Lunar Landers** – to deliver large payloads to propellant depot	Low	Low	Low	Low	High
Phase 2	**Propellant Depot in Cis-Lunar Space** – to store several tons of H2O or prop	Low	Low	Low	Low	High

Phased Development Approach for LCOTS

Phase 1 Surface Resources and Hazards Assessment:

- Demonstrate capabilities to transport payloads from Earth to Lunar Surface cost effectively.
- Prospect several sites for surface resources and hazards.
  - Provide ground truth data of various sites including volatiles, water-ice concentrations, sun illumination, thermal environments, etc.
  - Assess potential sites for hazards and accessibility, such as, rough terrain, dust, craters, etc.
- Demonstrate techniques for resource extraction and future ISRU operations

Phase 2 Lunar ISRU Demonstration:

- Demonstrate capabilities for ISRU resource production, such as, H2O, LOX, LH2, and storage on a pilot-scale program (1 or 2 metric tons of resource).
- Demonstrate feasibility and economics of scaling up production and capability to store several tons of resources on lunar surface.
- Demonstrate capability to transport large payloads from lunar surface to cis-lunar space destinations (such as, Earth-Moon Lagrange Points or Lunar Distant Retrograde Orbit) for long-term storage.

Phase 3 Lunar ISRU Production and Delivery Services

- NASA awards long-term contract for Lunar ISRU production of H2O or LOX/LH2 on the order of several metric tons per year.
- Awards are also made for delivery services to Cis-Lunar Depot.
- Awards are made to multiple commercial providers to reduce risk and enable competition.

Phase 1 Option 1:
Lunar Payload Delivery Services

- NASA purchases Lunar Payload delivery services to transport instrumentation package to lunar poles to ***obtain ground truth data***;
- Google Lunar XPRIZE (GLXP) and Lunar CATALYST teams are viable candidates for providing lunar lander and rover services after GLXP has been awarded;
- One option for the payload may be smaller version of Regolith & Environmental Science and Oxygen & Lunar Volatile Extraction (RESOLVE) instrumentation suite;
- Range in costs vary depending on the partnership agreement between LCOTS partners to share cost and risk to develop lunar transportation capabilities.

Resources Needed	Requirements	Potential Sources	Range in Cost for LCOTS Partners
Launch Vehicle	Launch payload to LEO and perform TLI to LLO;.	SpaceX – Falcon 9 ULA – Atlas V	\$30M to \$60M
Landers and Rovers	Deliver up to 270 kg to lunar surface.	GLXP Teams Lunar CATALYST teams	
Prospecting Instruments and ISRU demo equipment	Govt to furnish instruments and equipment.	Candidate instrumentation package: RESOLVE	\$20M to \$40M to deliver instrument payload
		Total Range in Cost	\$50M to \$100M

Phase 1 Option 2: Prospecting and ISRU Demos

- NASA partners with GLXP and CATALYST teams (post-GLXP award) to ***deliver multiple payloads to multiple sites on a single launch*** to demonstrate prospecting and ISRU capabilities;
- Instruments and equipment for demonstrations should be openly competed or supplied by GFE;
- Approach is more cost-effective and overall lower risk since multiple payloads are deployed on one single launch. However, safety and mission assurance risk is increased to each lander/rover system since multiple systems are being deployed together.

Resources Needed	Requirements	Potential Sources	Range in Costs for LCOTS Partners
Launch Vehicle	Launch payload to LEO and perform TLI to LLO;	SpaceX – Falcon Heavy ULA – Vulcan Rocket	\$50M to \$90M
Landers and Rovers	Deliver up to 5 lander/rover systems to lunar surface.	GLXP teams Lunar CATALYST teams	
Prospecting and ISRU demo equipment	Prospecting instruments to identify resources; ISRU equipment to demo capabilities, such as H2O extraction.	Shackleton Energy Moon Express Or GFE	\$20M to \$30M for each payload (up to 5)
		Total Range in Cost	\$150M to \$240M

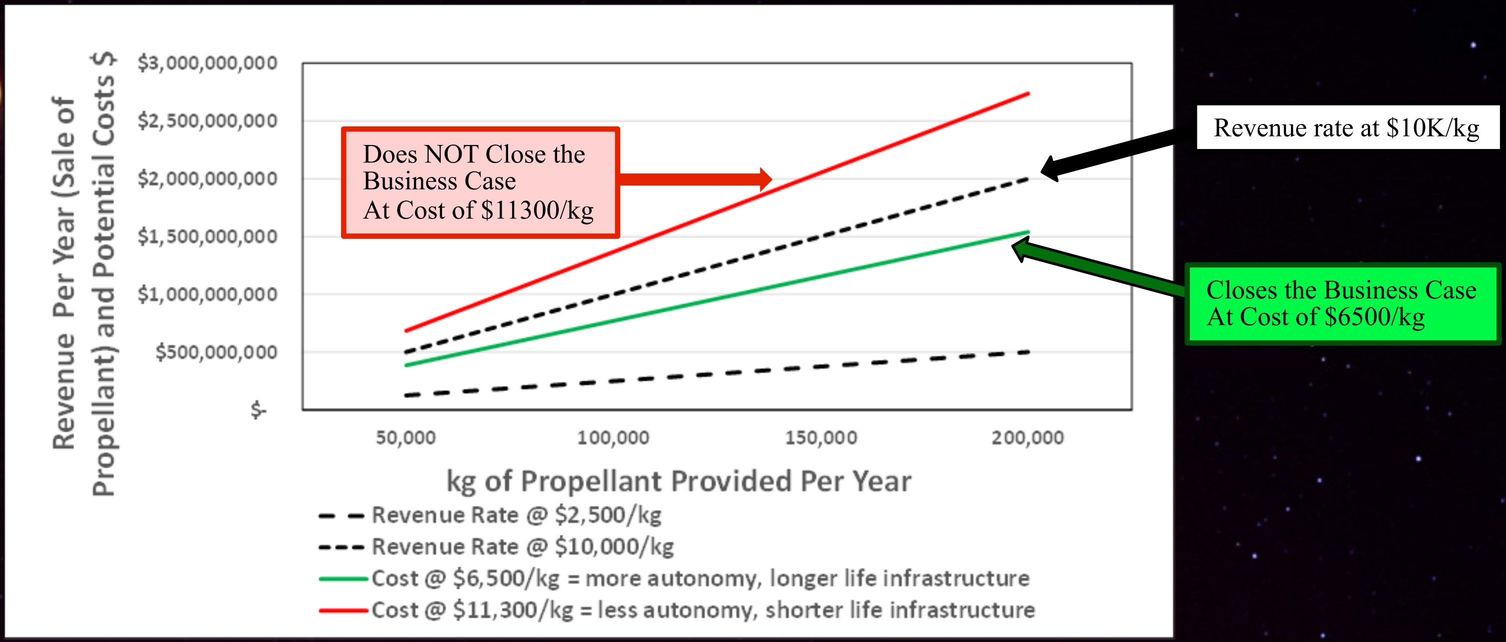
Phase 2 Option for Pilot Scale H2O Extraction Demonstration

- Demonstrate robotic operations of ISRU hardware for excavation, water cleaning, processing and storage of H2O found in polar water/ ice deposits (for pilot-scale demo of 1 or 2 metric tons);
- Assume polar site selection determined to be most economical from results of Phase I;
- Assume power stations and comm/nav satellites in place for polar operations;
- Other emerging lunar markets may drive recurring costs down for H2O production once successfully demonstrated.

Resources Needed	Description	Representative Companies
Launch Vehicle	Launch payload to LEO and perform TLI to LLO	SpaceX – Falcon Heavy ULA – Vulcan Rocket
Lunar Landers	Transport payloads (up to 2 mt) from LLO to Lunar Poles	GLXP Teams Lunar CATALYST Teams
Excavator/Hauler	Medium-size rover(up to 1 mt) to dig and move lunar soil from polar ice deposits to water processors.	Caterpillar
H2O Processing and Storage Tanks	Demo-size processor and tank (up to 1 mt) capable of storing up to 2 mt of water.	Shackleton Energy
	Total Estimated Cost	$350M to $400M

Economic Assessment of Lunar Propellant for Mars Mission

- Initial economic assessment was performed to assess viability of a business plan to produce lunar propellant (LOX/LH2) for a Mars transportation system.
- Assumptions were made to estimate ***Price Points*** for revenue stream vs. operational costs.
  - Price points for revenue will vary depending on market forces in the future. If there is high demand for propellant at LEO or other cis-lunar destinations, this will drive down price point for propellant.
  - Operational costs for ISRU production and delivery of propellant to cis-lunar destinations were estimated as $/kg. This price point will vary depending on level of autonomy vs human tending for ISRU operations.
  - Initial results showed it was feasible to close the business case for operating costs in the range of $6500/kg at a propellant price point of $10K/kg.
- Other benefits should also be considered, such as, risk reduction for future human Mars missions, and emergence of other cis-lunar markets, such as, lunar mining or lunar tourism.



Summary

- Authors recommend to continue investigation of a potential Lunar COTS program to support NASA's ultimate goal of sending humans to Mars.
- LCOTS Program Goals:
  - Establish affordable, cis-lunar capabilities and services by partnering with industry to reduce development and operational costs ***for mutual benefit***.
  - Enable NASA to develop an economical and sustainable exploration architecture.
  - Encourage creation of new markets in cis-lunar space to further reduce operational and life-cycle costs.
- Recommend to use NASA COTS acquisition model to ***effectively reduce development and operations costs***.
- Recommend phased-development approach to allow for incremental development and demonstration of capabilities with several off-ramps for a lower-risk approach to LCOTS.
  - Phase I will focus on providing ***ground truth data*** of lunar surface resources and hazards at several lunar sites including water-ice concentrations, volatiles, sun illumination, thermal environments, etc.
- Initial economic assessment was performed to assess viability of a business plan to produce lunar-derived propellant for a Mars transportation system.
- Although these findings are promising, ***follow-on work is needed*** to continue evaluating the benefits and challenges of a potential Lunar COTS program.

Forward Work

- Evaluate NASA's interests and possible investments available to develop cis-lunar infrastructure and capabilities ***in partnership with industry***.
- Continue evaluating the ***technical and financial viability of emerging space companies*** to meet requirements for a potentially, new LCOTS program.
- Refine demonstration objectives in Phased approach for industry to achieve and estimate development costs to achieve demonstrations.
- Determine govt incentives needed to encourage industry to pursue these commercial opportunities.
- Perform ***'Blue Ocean' market*** study to forecast emergence of new markets in cis-lunar space.
- Estimate the potential cost savings to NASA compared to more traditional project approaches.
- Perform economic analysis to determine impact to national and global economy as a result of new markets and industries on the Moon.


Questions?